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Quaternary stratigraphy of the tidal flats, King Sound, Western Australia

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Abstract

Six new stratigraphic units are recognised in the Quaternary sequence underlying the tidal flats of the southern portion of King Sound. The youngest, the Point Torment Sand, is a Holocene sequence of shoreline sandy spits; it overlies and interfingers with the Holocene Doctors Creek Formation (10–12 m thick) which is a shoaling-tidal-flat sequence comprising sands, sand/mud laminites and bioturbated mud. The Doctors Creek Formation unconformably overlies the Christine Point Clay (4–6 m thick), which is a Pleistocene mangrove-sediment unit. The Christine Point Clay rests on a thin palaeosol, termed the Double Nob Formation, which in turn rests on the oldest Pleistocene marine unit in the area, the Airport Creek Formation. This formation is composed of semi-lithified to indurated, tidal sand and mud laminites and beds. The Mowanjum Sand is the oldest Quaternary unit in the area; it rests unconformably upon lateritised Mesozoic rocks and underlies the Airport Creek Formation. Its margin has been reworked during later transgressive phases and it extends as tongues across the unconformity interfaces that separate the other Quaternary units. The tidal flats at present are undergoing rapid erosion and most of the Pleistocene and Holocene units crop out across vast, tidally-scoured surfaces. These surfaces are frequently covered by a thin, ephemeral sedimentary blanket termed the Modern Veneer. The Quaternary stratigraphy in the King Sound area reflects the sedimentary accumulation during 3 marine inundations. The Airport Creek and Christine Point Formations accumulated during 2 separate Pleistocene marine incursions. The Doctors Creek and Point Torment formations accumulated, and are accumulating, during the Holocene incursion.

Introduction

The Quaternary stratigraphy of the King Sound area in Western Australia has been left undifferentiated (Casey 1958; Gellatly and Sofoulis 1973). During the course of recent ecological and geological research on the tidal flats of King Sound the author subdivided the Quaternary sediments into numerous stratigraphic units. This paper describes the Quaternary sedimentary sequence underlying both the tidal flats and the adjoining hinterland and proposes stratigraphic nomenclature for the new units. The data and the stratigraphic framework are provided to the detail required for future work on sedimentology, geomorphic development and description of biological habitats of this area.

Methods

The stratigraphy of the area was investigated firstly along selected transect lines. The transects were profiled and levelled with respect to Australian Height Datum (AHD) which enabled later location of various stratigraphic levels relative to datum tide. Conventional methods of hand augering (to 5 m depth), vibrocoring (to 7 m depth) and augering with a Gemco rig (to 16 m depth) were used to explore stratigraphy along the transects. Location of transects and bore and core sites are shown on Figure 1.

At many localities however, stratigraphic units and their relationships are well exposed for direct observation and measurement. This is the case along the banks and walls of deeply incised tidal creeks where hundreds of metres of cliff section are exposed and washed clean by tidal waters. Extensive stratigraphic sections also are well exposed along cliffs parallel to the shore and across vast, tidal-scoured surfaces from which the sedimentary veneer has been stripped. Creeks and cliffs, where well exposed stratigraphic units were studied in detail, are located on Figure 1.

Geological setting

King Sound is a large marine embayment, of approximately 5 000 km², and is located in the Kimberley region of north Western Australia. Geologically, King Sound is a Quaternary depositional embayment within the Canning Basin. To the north King Sound is flanked by pre-Quaternary (Proterozoic to Tertiary) rocks and vegetated Quaternary red sand dunes and a rocky coastline with narrow tidal flats is developed (Casey 1958; Gellatly and Sofoulis 1973). To the south it is flanked by Quaternary sediments, such as vegetated red sand dunes, grassy alluvial plains and broad tidal flats; these Quaternary sediments overlie, at shallow depths, Mesozoic rocks and Tertiary ironstone (Casey 1958).

In the southern localities the tidal flats and adjoining hinterland are clearly zoned into several units using geomorphology and associated vegetative communities. From landward the units are:

1.—hinterland of vegetated red sand dunes and/or Mesozoic rock, or ironstone outcrops.

2.—supratidal and salt marsh flats, inundated by storm water and the highest tides.

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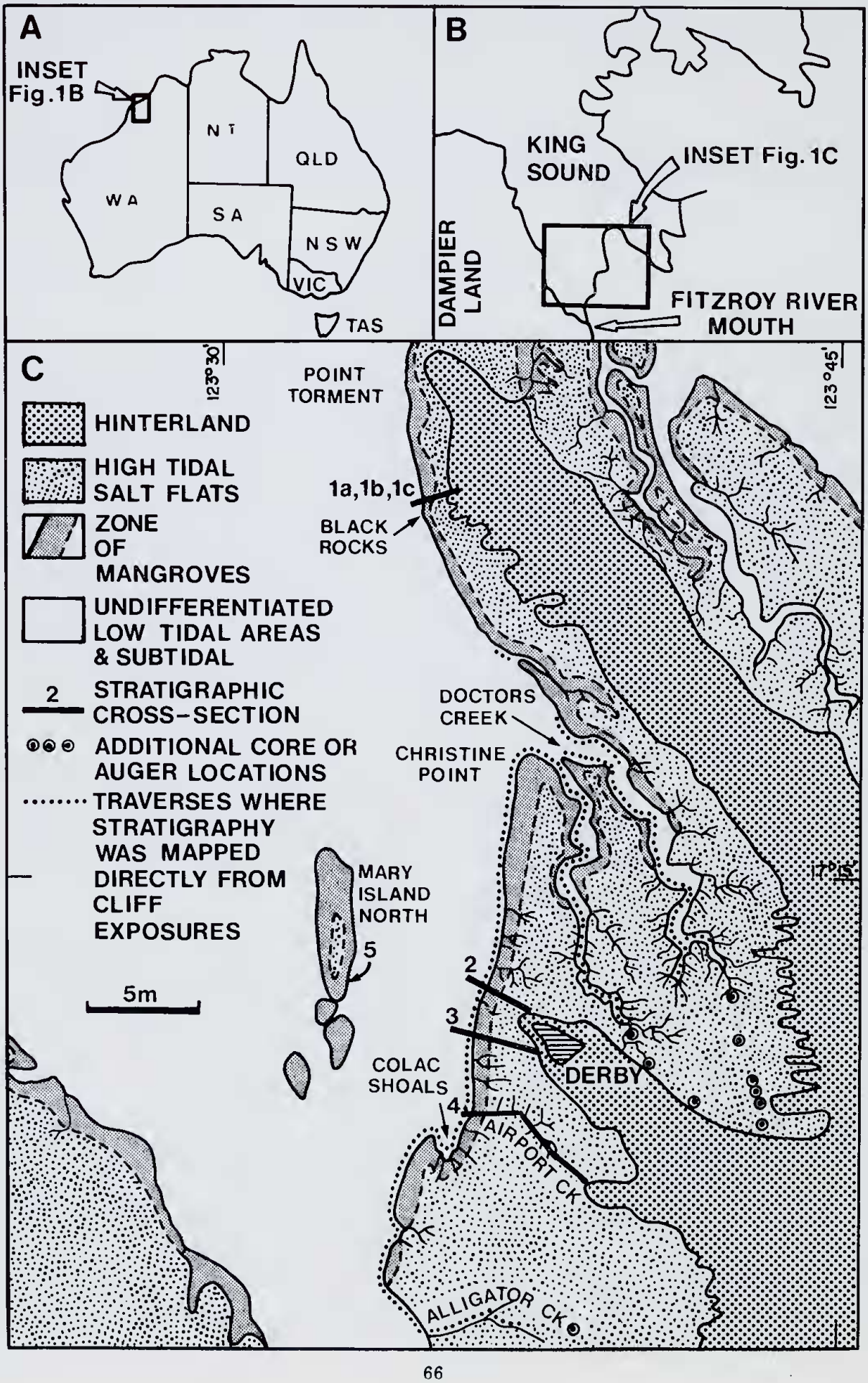
A
INSET Fig.1B
NT
QLD
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KING SOUND
INSET Fig. 1C
DAMPIER LAND
FITZROY RIVER MOUTH
C
123°30'
123°45'
17°15'
POINT TORMENT
HINTERLAND
HIGH TIDAL SALT FLATS
ZONE OF MANGROVES
UNDIFFERENTIATED LOW TIDAL AREAS & SUBTIDAL
2 STRATIGRAPHIC CROSS-SECTION
ADDITIONAL CORE OR AUGER LOCATIONS
TRAVERSES WHERE STRATIGRAPHY WAS MAPPED DIRECTLY FROM CLIFF EXPOSURES
5m
1a,1b,1c
BLACK ROCKS
DOCTORS CREEK
CHRISTINE POINT
MARY ISLAND NORTH
5
2
3
4
COLAC SHOALS
DERBY
AIRPORT CK
ALLIGATOR CK

3.—salt flat, occurring above mean high water spring.

4.—mangrove and salt marsh flats, which are vegetated surfaces occurring between mean sea level and mean high water spring.

5.—an inclined slope, occurring between mean sea level (or high water neap) and low water neap.

6.—low-tidal flats exposed by low water spring tides.

Mainly as a result of tidal erosion, modifications of the basic zonal sequence occur. Firstly, a small sea cliff may separate the inclined slope from the mangrove flats so that their junction then occurs at high water neap rather than at mean sea level. A small cliff may also separate the inclined slope from the low tidal flats. Secondly, rocky islands, rocky "reefs" and sand bars are present locally. Thirdly, tidal creeks are common on the flats and incise all but the highest tidal and supratidal levels.

Stratigraphy

Six Quaternary stratigraphic units are recognised underlying the tidal flats and onshore hinterland of the King Sound area. They are (in descending order):

6.—Point Torment Sand

5.—Doctors Creek Formation

4.—Christine Point Clay

3.—Double Nob Formation

2.—Airport Creek Formation

1.—Mowanjum Sand

In addition much of the eroded surface of the tidal flats is covered by an ephemeral, thin blanket or veneer of sediment termed the Modern Veneer.

Mowanjum Sand

The Mowanjum Sand is a unit of red dune sand that forms the onshore hinterland bordering most of the tidal flats of King Sound. The dunes are east-west oriented longitudinal forms fixed by *Eucalyptus* and *Acacia* shrublands and woodlands.

Derivation of name.—Mowanjum Mission; grid reference 130813, Derby 1:250 000 sheet.

Type section.—The type section is designated in a sand quarry (grid reference 128820, Derby 1:250 000 sheet) on the nothern margin of Derby townsite. Here a section, 6 m thick, is well exposed and a further 1 m was penetrated by auger.

Distribution.—The Mowanjum Sand forms an extensive undulating plain over 20 km wide bordering both eastern and western margins of King Sound for over 200 km; the areal extent of the Mowanjum Sand is well over 4 000 km^2. Locally, as at Black Rocks, the unit is cliffed and exposed on the low tidal flats. Numerous road-cuts expose cross sections of the longitudinal dunes along the Derby-Broome Highway. The formation is also penetrated in the numerous water bores in the Derby area.

Geometry and thickness.—The Mowanjum Sand is a sheet deposit that blankets Mesozoic and Tertiary rocks. Thickness varies depending on undulations in the underlying rocks. Maximum recorded thickness is 15 m in a small embayment on the west shore of King Sound (grid reference 688805, Derby 1:250 000 sheet) opposite Alligator Creek (Jennings 1975). Locally because of subcropping Tertiary rock highs, its thickness is less than 1 m.

Lithology.—The formation is composed mainly of red to orange quartz sand; locally the sand is white. There are sheets and wedges of white sand, ferruginised sand and root-structured sand interlayered locally with the main red sand. The structure is homogeneous to mottled to (locally) root-structured; animal burrows are common in the upper parts. Fe-oxide mottles and/or orange clay mottles are scattered but abundant in some areas. Parts of the formation have been cemented by Fe-oxide forming ferruginous sandstone as sheets and along former root casts.

Fossils.—The formation contains only trace fossils (animal burrows, root casts) and scattered plant detritus.

Stratigraphic relationships.—The Mowanjum Sand rests unconformably on Tertiary laterite and other pre-Quaternary rocks. The formation can be observed beneath all other Quaternary formations where it is well exposed in low tidal areas. Coring indicates that the Mowanjum Sand preceded the younger Quaternary formations (Figs. 2 and 7). The depositional breaks between the younger formations are marked by sheets of red sand, white sand (= marine reworked red sand), or bioturbated muddy sand (= marine reworked Mowanjum Sand bioturbated by a mangrove community). These sand (or muddy sand) sheets are extensions of the main Mowanjum sand body (Fig. 2) and pinch out seaward. In many localities successive marine incursions during the Quaternary have completely eroded the seaward edge of the Mowanjum Sand and the younger formations rest directly on Tertiary rocks (Fig. 7).

Discussion.—The Mowanjum Sand is essentially a sand-plain (terrestrial) formation probably of aeolian origin. Its present geomorphic surface has been shaped by aeolian activity. Along the shores of King Sound the top of the unit occurs from levels of over 30 m above high tide down to the low spring tidal zone. On its seaward margin the Mowanjum Sand has been reworked by successive marine trangressions and there are ribbon to sheet extensions intercalated with marine units. The extensions (reworked margins) were formed by a combination of sheet-washing of sand across plains during wet seasons and marine reworking of the exposed edge of a sand plain.

Airport Creek Formation

The Airport Creek Formation is a unit of semi-lithified and nodular-cemented interlayered sand and mud deposited in Pleistocene tidal environments. The unit forms extensive sheet outcrops exposed at low spring tides.

Derivation of name.—Airport Creek, which is a tidal creek draining high tidal flats west of Derby airport and Mowanjum Mission. Grid reference (for mouth of creek): 121817, Derby 1:250 000 sheet.

Type section.—The type section is designated as the mouth and banks of Airport Creek; here 3 m of section and the contact with the overlying formation are well exposed. The base of the unit is not exposed.

Distribution.—The formation crops out over 8 km^2 of tidal flat exposed at low tide between the mouth of Airport Creek and Nob Hillock. The unit is observed

Figure 1.—Map showing location of study area. Inset C shows transect lines, position of additional core or auger sites and traverses.

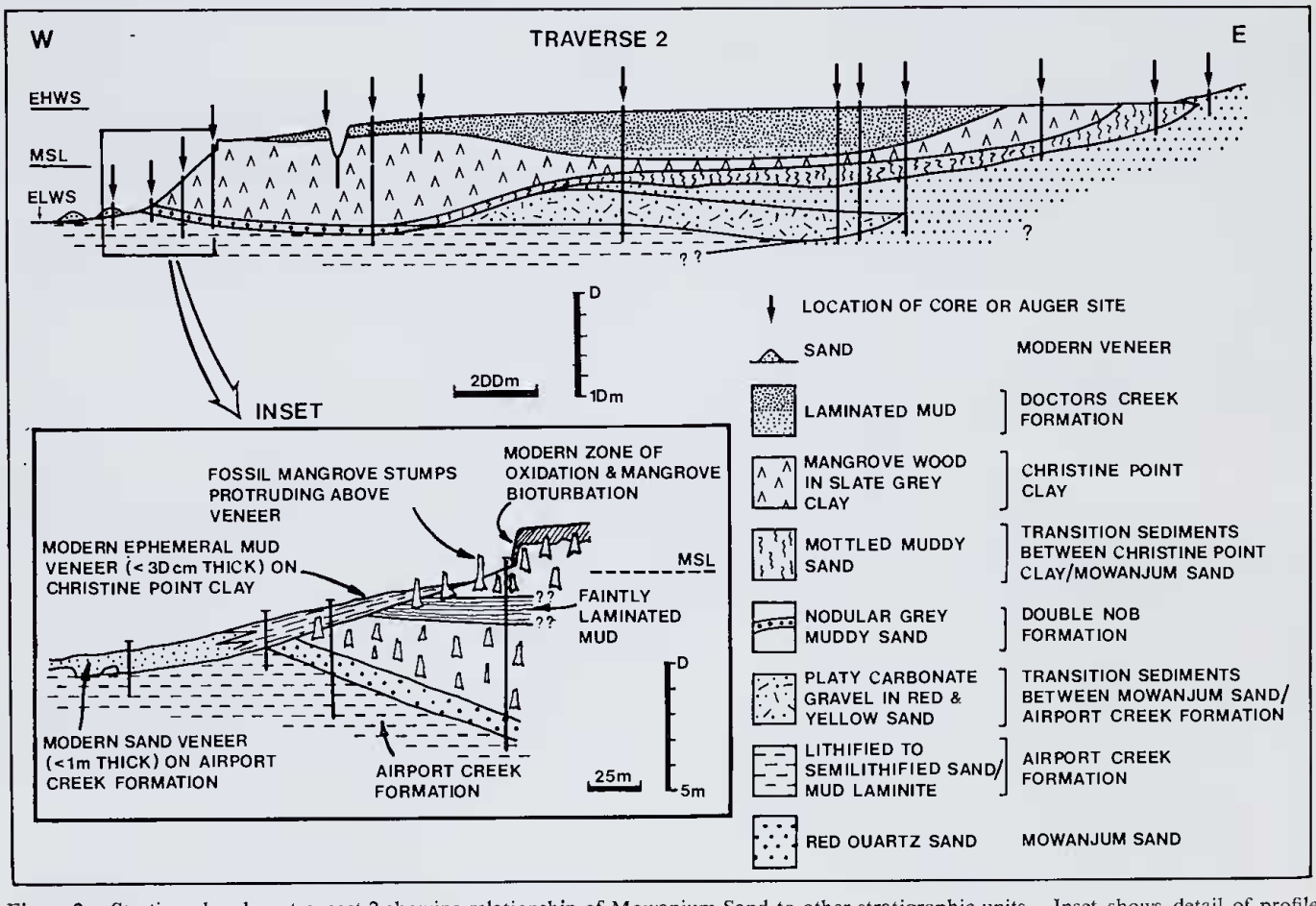

Figure 2.—Stratigraphy along transect 2 showing relationship of Mowanjum Sand to other stratigraphic units. Inset shows detail of profile exposed on shore face at Derby Jetty.

in small outcrops several kilometres offshore from Derby during periods of the lowest tides. It crops out on the floor and banks of Airport Creek and Doctors Creek where the Modern Veneer is stripped away. Additionally the formation has been intersected in cores at various sites (transects 2, 3 and 4). It is inferred from its distribution pattern that the formation underlies most of the tidal flats and that it covers an area of over 200 km².

Geometry and thickness.—The geometry of the Airport Creek Formation is incompletely known because the total thickness is unknown except for onshore sections. Numerous cores and outcrops, however, show that the top of the formation is extensively eroded with broad scours up to 4 m deep.

The unit typically is exposed between intervals of low water neap and shallow subtidal, i.e. over 3 m, which is its average exposed thickness. Coring along traverse 2 (Fig. 2) shows that the unit is at least 8 m thick; the base however was not reached.

Lithology.—The formation is composed of a grey to buff, semi-lithified to indurated, sediment suite that includes: (a) laminated, cross-laminated and ripple-laminated sand; grains are mainly quartz and calcareous skeletons, (b) laminated, cross-laminated and ripple-laminated silt; grains are quartz and skeletons, (c) laminated and bedded clay, (d) burrow-structured to bioturbated sand, silt and clay. The sediments typically are interlayered and interlaminated; sand predominates in the suite. The induration or semi-lithification is due to an interstitial precipitate of low-magnesian calcite.

Fossils.—The formation contains three types of fossils: (a) abundant microfauna, as grain types in the sand and silt, including foraminifers, sponges and mollusc fragments, (b) scattered macrofauna of crab claws and debris (*Uca* spp., *Scylla serrata*), bivalves, (c) an ichnofauna that includes burrow traces of crustaceans and worms.

Stratigraphic relationships.—The Airport Creek Formation appears to rest unconformably on Mowanjum Sand or Tertiary laterite. On low tidal flats in the Derby area the base of the unit is not exposed. Coring further onshore (Figure 2) indicates that the formation rests on Mowanjum Sand; the Airport Creek Formation usually is reduced to an aggregate of reworked nodules (transition sediments of Figure 2) above the Mowanjum Sand. Further north at Black Rocks the same stratigraphic relationship is exposed at low tide, i.e. an aggregate of "limestone" nodules (presumably formed as a lag after erosion of Airport Creek Formation) rests on Mowanjum Sand. The top of the Airport Creek Formation is gradational into the overlying Double Nob Formation. Locally, erosion has removed the Double Nob Formation and the Airport Creek Formation is overlain, with sharp contact, by the Doctors Creek Formation (Figs 2, 3 and 4).

Discussion.—The Airport Creek Formation is essentially a lithified to partly lithified tidal flat sedimentary accumulation. The sediments all have analogs on the modern tidal flats particularly in low to mid tidal levels. The interpretation of the stratigraphic relationships between Airport Creek and other formations in many

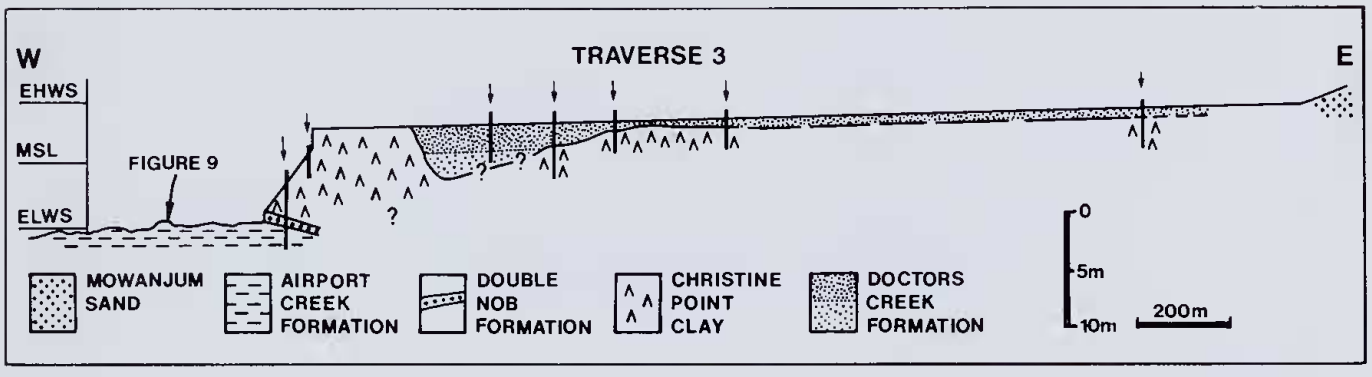

Figure 3.—Stratigraphy along transect 3 showing relationship between Doctors Creek Formation and Christine Point Clay.

areas depends upon recognition of pebbles derived from the formations. Erosion of Airport Creek Formation typically results in a lag of grainstone-lithoclast pebbles that are usually platy. These pebbles represent the indurated parts of the formation that remain as residuals during erosion (Fig. 9). Similar pebble lags develop where nodular-cemented younger formations are eroded but, in contrast, the Airport Creek nodules retain the distinctive lithology and sedimentary structures, and furthermore are indurated by low-magnesian calcite cement. Younger formations are predominantly composed of bioturbated or massive mud and are patchily indurated by magnesian calcite, dolomite and aragonite cements.

Double Nob Formation

The Double Nob Formation is a sheet of black nodular soil that separates the Airport Creek and Christine Point Formations.

Derivation of name.—Double Nob Hillock (grid reference 821121, Derby 1:250 000 sheet).

Type section.—The type section is designated on the low tidal flats 1·5 km south of Derby jetty (traverse 3 on Fig-1) where the base and top of the unit are well exposed (Fig. 8).

Distribution.—The formation is exposed in over 9 km of cliff section at levels of low tide from the mouth of Airport Creek northwards. It also occurs in scattered outcrops and cliff sections wherever the base of the Christine Point Clay is exposed. Additionally the unit has been intersected in a few core sites (traverses 2, 3 and 4).

Geometry and thickness.—The Double Nob Formation is a thin (sheet) unit that blankets the Airport Creek Formation. Its thickness varies from 30 cm to 1 m.

Lithology.—The unit is composed of homogeneous dark grey muddy sand cemented by low magnesian calcite into granule-sized nodules; sand grains are medium and coarse quartz.

Fossils.—The unit is unfossilferous.

Stratigraphic relationships.—The Double Nob Formation overlies the Airport Creek Formation with gradational contact. The unit underlies the Christine Point Clay and the contact varies from sharp to gradational; gradational contacts are characterized by a transitional zone (up to 20 cm thick) composed of burrow mottles, root structures, and biogenic mixing of formation boundaries.

Discussion.—The lithology (texture, composition and colour) of the Double Nob Formation is similar to inland black soils on the modern plains bordering limestone ranges of the Kimberleys (Playford and Lowry 1966). The granule-sized nodules in the unit are $CaCO_3$ indurations and probably are pedogenic. Similar pedogenic $CaCO_3$ nodules occur locally in black soils inland in the Kimberleys. The Double Nob Formation probably represents a pedogenic unit developed on a calcareous parent (Airport Creek Formation) during a Pleistocene low sea level stand. At the time the King Sound area would have been an extensive undulating savannah plain (some 2·5–3 m below present mean sea level) underlain by black soil.

Christine Point Clay

The formation is composed of a grey clay with abundant *in situ* large mangrove stumps. It is a distinctive unit well exposed on the eroding tidal flats around Derby.

Derivation of name.—Christine Point (grid reference 123834, Derby 1:250 000 sheet).

Type section.—The type section is designated on the mid to low tidal flats 1·5 km south of Derby jetty (Traverse 3, Fig. 1) where the base and most of the unit are exposed (Fig. 8).

Distribution.—The formation is exposed in cliff sections at numerous localities along the coast between the mouth of Airport Creek and Christine Point and in Airport Creek, Doctors Creek and the creeks north of Derby jetty. The formation has been intersected in numerous cores in traverses 1–4, and occurs over 100 km² in outcrop and subsurface on the eastern shore of King Sound.

Geometry and thickness.—The geometry of the formation is incompletely known because its seaward extremity has been eroded away; the unit also has been extensively eroded and scoured prior to deposition of the overlying formations. The Christine Point Clay largely appears now as isolated buried islands or hinterland-fringing platforms (Fig. 6). From a consideration of the enveloping surface of its base and top, it appears that the unit was deposited on a sloping to undulating surface. The maximum thickness of the unit is 7·5 m. Generally the unit is 4–6 m thick at its present western (eroded) margin and it thins toward the hinterland (Figs. 2, 3, and 4). The formation was essentially wedge-shaped and fringed the hinterland prior to extensive erosion.

Lithology.—The formation is mostly uniform throughout its thickness and is composed of slate grey, homogeneous to mottled clay; large *in situ* mangrove stumps (up to 1·2 m diam), rootlets and plant detritus are abundant; locally there are filled burrow structures. There is local development of nodules by precipitates

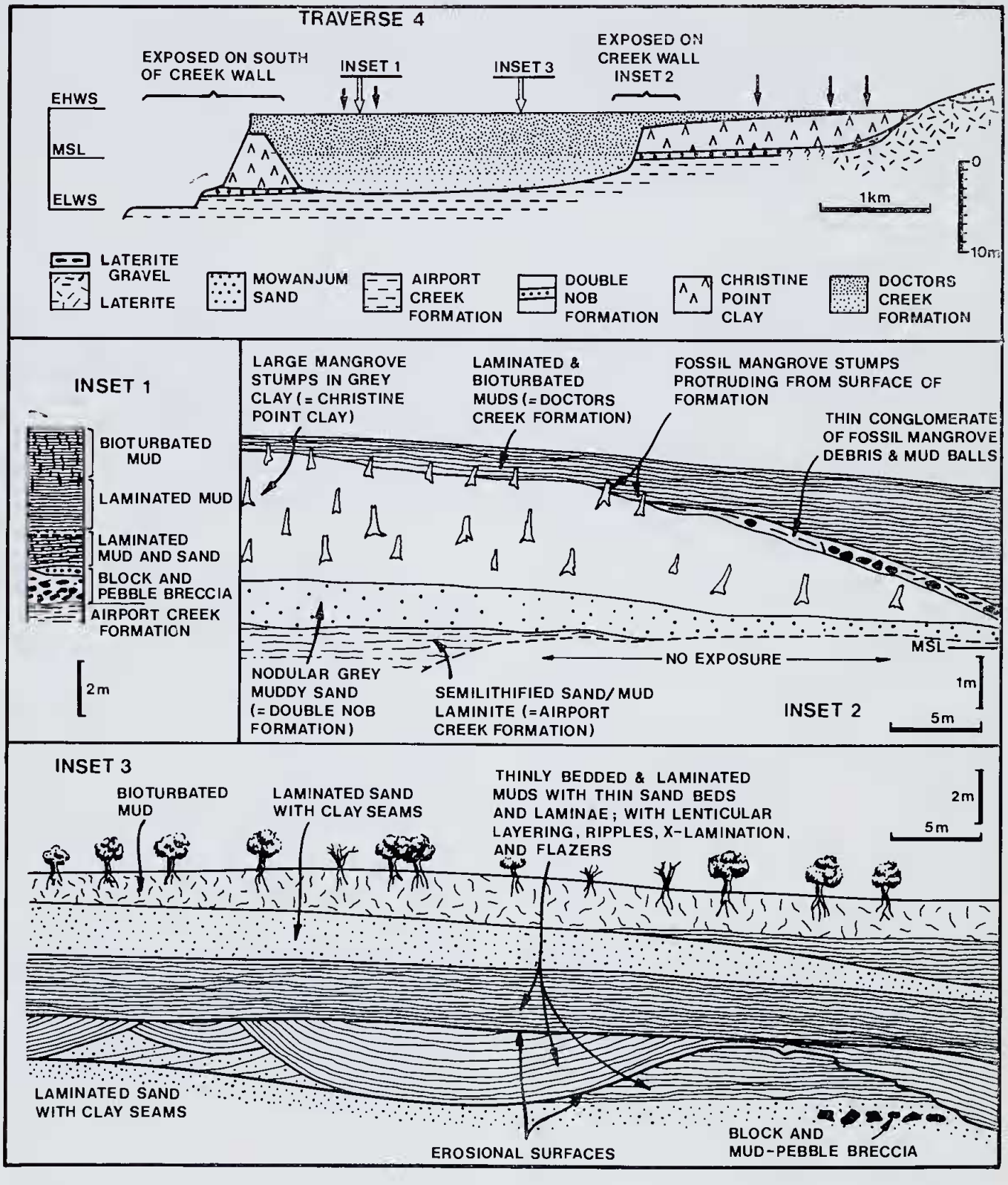

Figure 4.—Stratigraphy along transect 4 (Airport Creek); arrows show locations along the creek where more detailed study was made of stratigraphic sequence. Insets show detail of stratigraphic relationships at various localities along the profile. Inset 2 is a view to the south of the creek wall.

of dolomite and magnesian calcite. A transitional sediment is developed between the contact of the Christine Point Clay and Mowanjum Sand. It is a grey, brown to orange, colour-mottled and burrow-mottled mixture of sand, muddy sand and mud. At about the middle of the formation there is a 1 m thick band of crudely laminated light grey clay without *in situ* rootlets and without the bioturbation features so typical of the rest of the formation (traverse 2, Fig. 2). This clay pinches out to the east.

Fossils.—The Christine Point Clay has yielded a variety of fossils. Imbedded in the formation are abundant *in situ* and reworked mangrove stumps and trunks (Figs. 8B and 8C), and calcareous to dolomitic nodules that contain a varied invertebrate fauna. The mangrove trunks and stumps have been identified as *Avicennia marina*, *Rhizophora stylosa* and *Ceriops tagal* (using root morphology, Field Key 2 of Semeniuk *et al.* 1978). The stumps and trunks of *Avicennia marina* are commonly riddled with carbonate-cemented borings referrable to *Teredo* spp.; the mangrove wood is locally impregnated with dolomite and/or magnesian calcite. Fauna from the nodules includes: *Uca* (fiddler crab), *Scylla serrata* (mangrove crab) and *Thalassina anomala* (mud lobster). Ichnofauna includes a wide range of indeterminate filled burrows.

Stratigraphic relationships.—The formation generally rests with gradational contact along its hinterland margins on Mowanjum Sand with a transitional zone of orange and grey sand mottled with brown muddy sand and clay. Seaward, the Christine Point Clay unconformably overlies the Double Nob Formation. The contact is sharp but varies locally to gradational with a transitional zone (a few decimetres thick) where sediments of the Christine Point Clay and Double Nob Formation are biogenically mixed by root casts and burrows. Locally *in situ* stumps that grew on the Double Nob soil are preserved.

The contact of the top of the formation with younger formations (Doctors Creek and Point Torment formations) is generally sharp where developed between mean sea level and low tide because biogenic activity is not as pervasive and has not disturbed the contacts. The top of the Christine Point Clay has either a sharp or gradational contact with overlying units at levels between mean sea level and high tide. The contact is usually sharp where it is above the range of modern mangroves, and is often marked by a weathered zone of oxidised clay and oxidised mangrove stumps. However the contact is gradational where root structuring, root casting and animal bioturbation has taken place (usually within the interval of modern mangrove growth i.e., about mean sea level to mean high water spring).

The base of the Christine Point Clay rests on the gently undulating top of the Double Nob Formation, some 2–3 m below mean sea level. Contact relationships indicate that the sea transgressed a soil plain and mangroves encroached upon and colonised the plain as it was inundated. The top of the formation is extensively and deeply scoured. The bulk of the Doctors Creek Formation occurs within these scoured hollows (Fig. 6). The contact is often marked by mud pebble conglomerate and mangrove wood debris.

Discussion.—The Christine Point Clay is a unit deposited largely under mangrove cover. The thin clay unit in the middle of the formation is lithologically and structurally similar to sediment formed today in mid-tidal (front of mangrove) environments. It would appear therefore that the Christine Point Clay represents an accumulation of sediment under transgressive, followed by regressive, conditions. The height of the transgression is represented by the mid-tidal clays that occur some 1·5–2·2 m below present mean sea level (Fig. 2).

The top of the formation has been weathered and planed to levels of high water spring and overlain by Doctors Creek Formation (Fig. 3). The bulk of the Christine Point Formation however was deeply scoured (probably by the Holocene transgression) and the large erosional hollows became embayments for deposition of Doctors Creek Formation (Figs. 2, 3, 4, 6).

Doctors Creek Formation

This unit is characterised by a shoaling sequence of sand, mud/sand laminite, bioturbated mud, and laminated (to vesicular) mud. The formation occurs locally in depositional embayments, where it is presently accumulating, but it is also undergoing erosion in many other localities where its depositional phase has ceased. The lithologies and their levels relative to datum can be correlated with modern tidal facies.

Derivation of name.—Doctors Creek (grid reference 125835 to 129821, Derby 1:250 000 sheet) where the unit is well exposed.

Type section.—The type section is designated along the banks of Doctors Creek between (grid reference) 125835 and 126830 (Derby 1:250 000 sheet).

Distribution.—The formation is exposed over 180 km^2 (Fig. 6). It is well exposed on the coastline and creeks south of Airport Creek, along most of the length of both channels of Doctors Creek and at the margins of Mary Island North. The formation occurs as a contemporary depositional unit in the Colac Shoals area (Fig. 1), in the stretch of coastline between Christine Point and Point Torment, and also in local embayments along the shore of Mary Island North. It has been intersected in core in traverses 2, 3, 4, 5 (Figs. 2, 3, 4, 5).

Geometry and thickness.—The formation occurs as large lensoid bodies 10 km x 10–15 km x 12 m as sedimentary fill in older tidal embayments; it occurs as ribbon to wedge-shaped bodies 10–15 km long, 2–4 km wide and up to 12 m thick fringing the coastline where it is currently accumulating; it also forms offshore lensoid shoals up to 10–15 km long, 4 km wide and 12 m thick as at Mary Island North, Mary Island South and Colac Shoals (Fig. 1).

Lithology.—There are essentially five main facies in the formation: (a) sand and shelly sand (b) sand/mud laminite (c) bioturbated mud (d) laminated mud (e) conglomerate.

The sand and shelly sand facies are laminated to cross-laminated, medium to coarse, quartz skeletal sediments; locally they are lithoclastic. Shells are abundant in bands and along laminae. Vertical burrows are scattered in occurrence.

The sand/mud laminite facies consists of interlayered sand and mud (Fig. 8D); the layers are centimetres to millimetres apart. Wavy lamination, lenticular bedding, flazer bedding, ripple-drift-lamination and cross-lamination (Reineck and Singh 1973) are typically present. Vertical to sub-vertical burrows (filled with sand or mud) are common and cut across layering. The mud bands and laminae are generally homogeneous to crudely laminated. Mangrove roots and scattered stumps are present toward the top of this facies.

The bioturbated mud facies is a root-structured, root-casted, animal bioturbated, to homogeneous mud unit. Locally it is crudely laminated. *In situ* man-

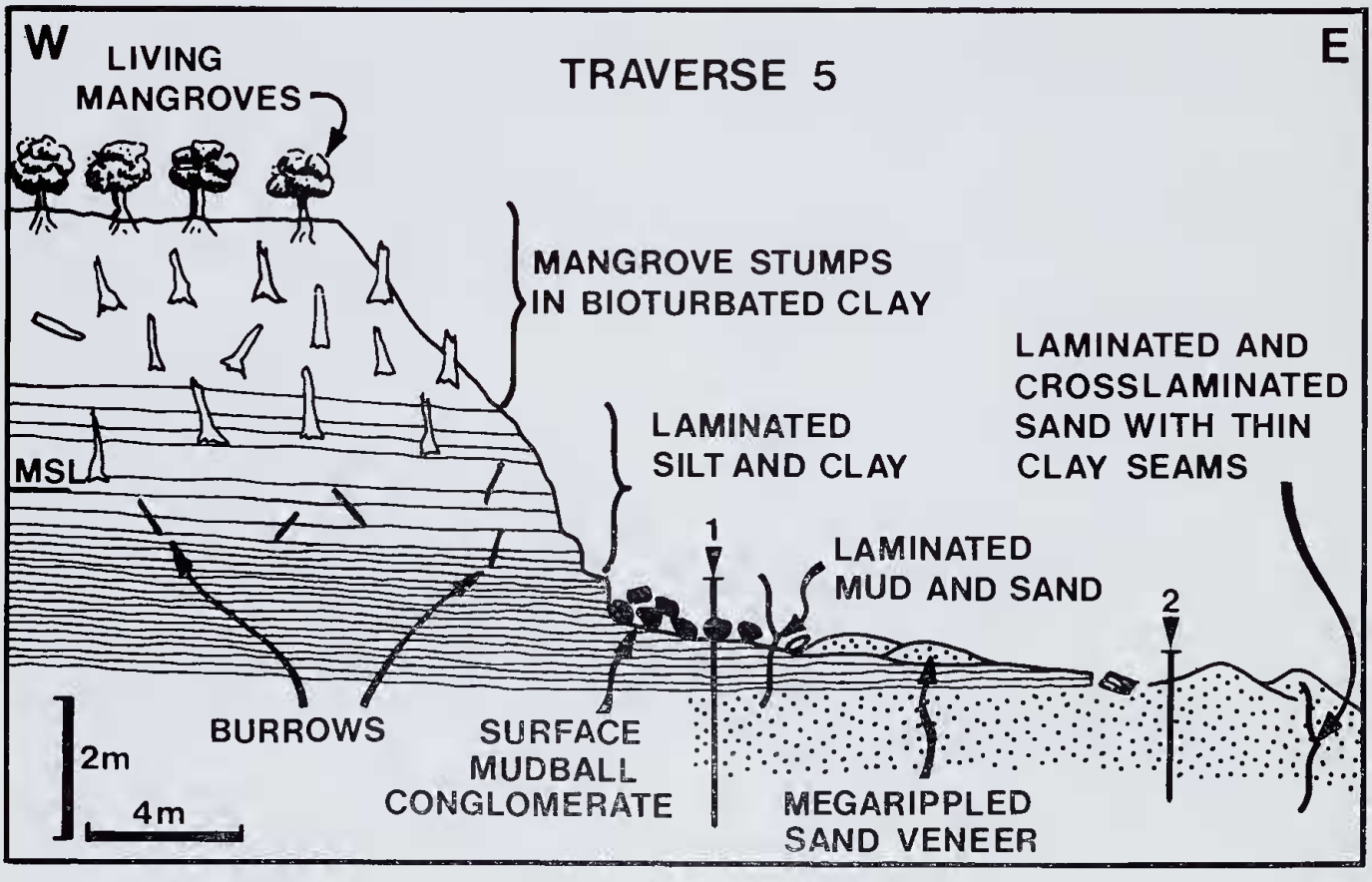

Figure 5.– Stratigraphy of Doctors Creek Formation along transect 5 at Mary Island North.

grove stumps and rootlets are common (Fig. 8D). Locally there are shell and sand lenses generally less than 10 cm thick; sand and shell are present either in discrete patches as burrow fills or scattered through the sediment. Locally there is patchy lithification by dolomite and magnesian calcite forming nodules (up to 20 cm in size).

The laminated mud facies is an interlayered silt and clay sediment. Laminae often are vesicular. Where silt is generally absent clay is crudely laminated and more obviously vesicular. Desiccation cracks and thin mud chip breccias are locally preserved in this facies.

The conglomerate facies forms a minor part of the formation but is important historically. There are three types of conglomerate, limestone-pebble, mud-clast and wood-debris, all with a grain-support gravel framework and interstitial mud. Limestone-pebble conglomerate is an accumulation of nodules eroded from the Airport Creek, Double Nob and Christine Point Formations (Fig. 4). Mud-clast conglomerate is composed of pebble- to boulder-sized clasts of mud eroded from Christine Point Clay, or intraformationally from eroding mud beds in the Doctors Creek Formation (Figs. 4 and 5). Mangrove-wood-debris conglomerate is a chaotic accumulation of mangrove stumps, trunks and branches (ranging in size from a few centimetres to over a metre), mixed with mud clasts and rarer limestone pebbles. The mangrove debris forms a supportive frame with the other pebble types. The facies in the Doctors Creek Formation are in a sequence that is related to modern tidal levels (Figs. 4, 5, 8) The sand and shelly-sand facies generally forms the lower parts of the formation in the interval of shallow subtidal to low water neap. This facies, with increasing mud content (mud seams), passes gradationally up into sand/mud laminite facies which occurs between intervals of low water neap and about mean sea level. Sand/mud laminite facies is, in turn, overlain by bioturbated mud facies the top of which is at mean high water spring; the contact is gradational and reflects decreasing sand and increasing bioturbation. The laminated mud facies occurs between levels of mean high water spring and the highest tides. Each facies thus is essentially sheetlike and stacked one upon the other:

top: laminated mud facies (< 1 m thick)
bioturbated mud facies (3–4 m thick)
sand/mud laminite facies (2–3 m thick)
bottom: sand and shelly sand facies (3 m or more thick)

Two exceptions to the sequence may be developed. Firstly, sand and shelly sand may form isolated ribbon bodies within the sand/mud laminite facies. This feature has its modern analog where a shoal (ribbon) of sand some 1–2 m thick has migrated into the sand/mud laminite lithotope. Secondly, the bioturbated mud facies locally may be poorly developed and laminated mud facies is present in its place. This relationship has its modern analog along the coast where mangroves are absent or sparse and sediments of the mid to high tidal flats are not intensely burrowed or root structured.

The conglomerate facies occur in the following stratigraphic locations. Limestone-pebble conglomerate generally is present as a lens- to wedge-shaped body (less than 1 m thick) where the Doctors Creek Formation rests on the Airport Creek or Christine Point formations. Mud-clast conglomerate occurs as

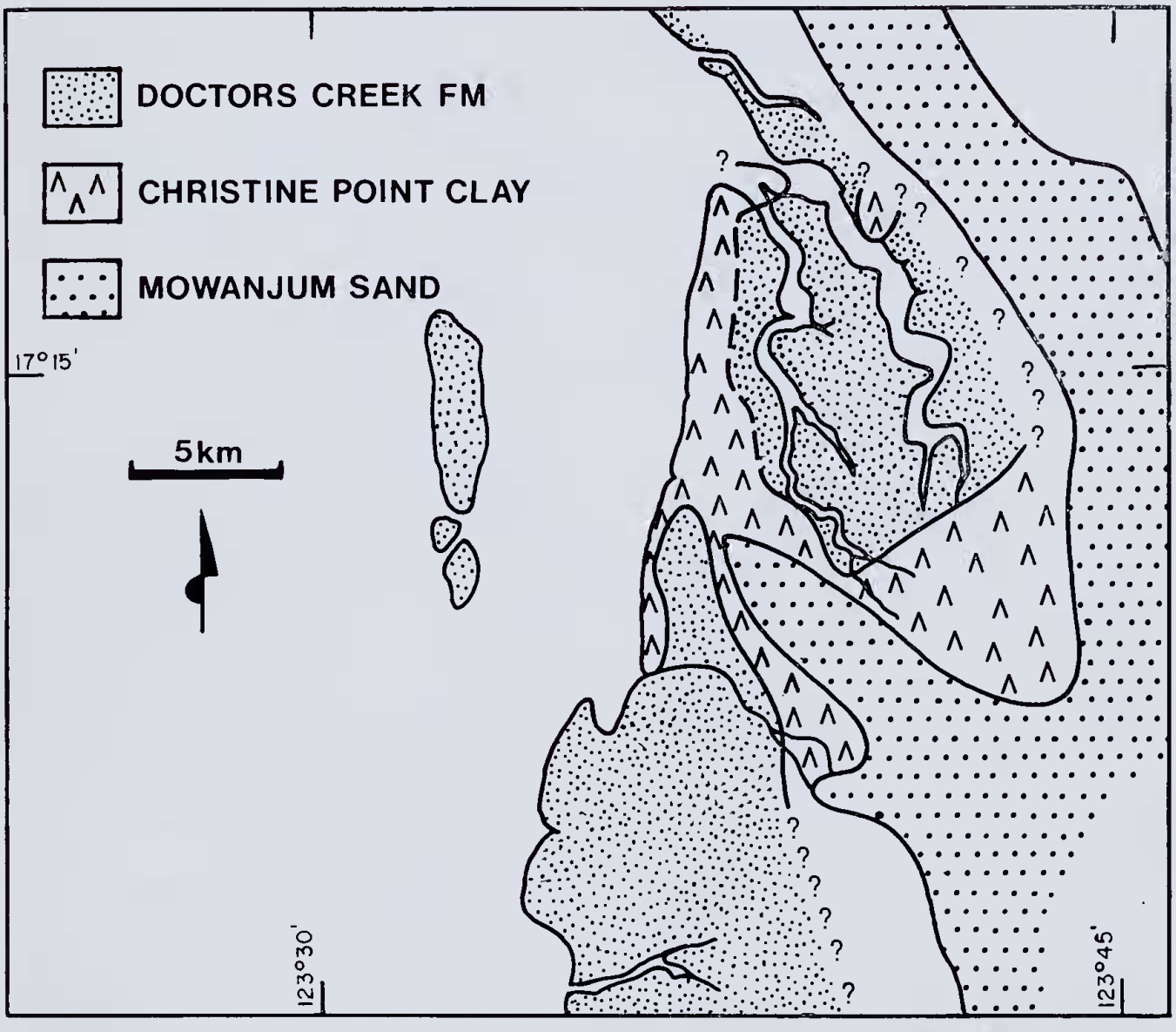

Figure 6.—Map showing distribution of Doctors Creek Formation in the large-scale hollows scoured out of Christine Point Clay. Boundary of Christine Point Clay and Doctors Creek Formation is illustrated in profile of transects 2, 3, 4 and Figure 8 C.

a lens (or wedge) deposit where the Doctors Creek Formation rests on, or abuts against, Christine Point Clay (Fig. 4); the conglomerate also forms as intraformational units where erosion of mud beds has taken place (Fig. 5). Mud clasts of intraformational origin are distinguishable microscopically, texturally and by colour from clasts eroded from the Christine Point Clay. Mangrove debris conglomerate forms lens- to wedge-shaped accumulations along the interface between the Christine Point Clay and the Doctors Creek Formation (Fig. 4) and at the mouths of tidal creeks that erode into a variety of formations.

Fossils.—The Doctors Creek Formation contains a variety of fossils. Flora includes *in situ* stumps of *Avicennia marina*, *Rhizophora stylosa* and *Ceriops tagal*. Diameter of stump rarely exceeds 10–15 cm. *Avicennia* and *Rhizophora* stumps and reworked trunks are often riddled with *Teredo* borings.

The most important and diagnostic fauna includes: (a) sand and shelly sand facies: molluscs *Barbatia*, *Saccostrea* fragments, *Nucula*, *Spisula*, *Solen* and *Zeuxis dorsata*; echinoderm tests and fragments; *Scopimerina* crab burrows as ichnofauna, (b) sand/mud laminite facies: sand laminae contains shell fauna as above; ichnofauna of the crabs *Uca* and *Macrophthalmus*, shrimps and worms, (c) bioturbated mud facies: molluscs *Telescopium telescopium*, *Terebralia sulcata*, *Cerithidea*, *Littorina scabra*, *Saccostrea*, *Nerita lineata;* crustaceans *Uca* spp., *Sesarma* spp, *Scylla serrata*, *Thalassina anomala*, barnacles and shrimps; an ichnofauna of borings and burrows of crustaceans, bivalves and worms, (d) laminated mud facies: crab claws, *in situ* bivalve *Glaucomya* sp; ichnofauna of crab, worm and insect burrows.

Stratigraphic relationships.—The Doctors Creek Formation rests erosionally and unconformably on all other older formations (Figs. 4, 6, 7, 8). The formation is best developed as sedimentary fill in large-scale hollows scoured into the Christine Point Clay (Fig. 6). The stratigraphic relationship here is erosional; mangrove stumps of the Christine Point Clay protrude into the overlying Doctors Creek Formation (Fig. 8C) and

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wedges of conglomerate are present above the contact. The erosional contact between Doctors Creek Formation and the Airport Creek and Double Nob Formations is also marked by conglomerate with debris reworked from the underlying units (Fig. 4).

Discussion.—The sedimentary facies of the Doctors Creek Formation have analogs on the modern tidal flats. Indeed the boundary between each facies corresponds to the tidal levels of the modern facies. Clearly the Doctors Creek Formation developed while sea level remained mostly at its present position. The sedimentary material that fills the large scale embayments (now buried under tidal flats) however is currently being rapidly eroded. It appears that most of the deposition of the formation ceased sometime earlier in the Holocene. Deposition of the formation continues in small, local, (semi-protected) embayments but these are minor features when compared to the large scale erosion occurring along the coastline.

Point Torment Sand

The Point Torment Sand is a unit of sand and shelly sand that generally borders the hinterland at levels of high tide. The formation is developed as shoreline spits typically to the north of Christine Point. The surface of many of the spits is above tidal levels and is colonised by terrestrial coastal vegetation such as *Acacia* and *Spinifex longifolia.*

Derivation of name.—Point Torment (grid reference 117853, Derby 1:250 000 sheet).

Type section.—The unit and its stratigraphic relationships are well developed at Point Torment Light Tower (grid reference 120847, Derby 1:250 000 sheet) and this locality is designated as the type section.

Distribution.—The formation is a discontinuous shoreline deposit along the east shore of King Sound between the north bank of the mouth of Doctors Creek and Point Torment, and north of Point Torment on both east and west shores of King Sound.

Geometry and thickness.—The formation is a series of spits essentially shoestring in shape (Jennings and Coventry 1973). These spits are aligned along the tidally-eroded edge of the Mowanjum Sand. The spits may exhibit splays across the depositional slope but they do not form a continuous north-south body. Individual spits are up to 1·5 km long and their width varies from a few metres to over 20 m. Splays occur over a total width of about 200 m. Maximum thickness of the spits is 3 m; subaerially and tidally degraded spits are less than 1 m thick.

Lithology.—The formation consists of cross-laminated, cross-bedded and, very locally, bioturbated, medium and coarse quartz skeletal sand, shelly sand and lithoclastic sand.

Fossils.—The fauna of this formation includes a large range of molluscs (listed in Doctors Creek Formation), crustaceans and corals. It represents material reworked from tidal communities in mangroves and offshore, as well as shell fragments (oysters and mud whelks) that probably are aboriginal middens.

Stratigraphic relationships.—The Point Torment Sand abuts the Mowanjum Sand (Fig. 7). The formation locally overlies and interfingers with modern sediments of the Doctors Creek Formation (Fig. 7). The Point Torment Sand is developed as spits along an eroding coastline cut into the finger-like extensions of Mowanjum Sand. The sand spits, transported by longshore tidal currents, migrated north and south from their source and developed three types of stratigraphic relationship with the contemporary Doctors Creek Formation: (a) an interfingering relationship with bioturbated mud (the mangrove lithotope) and laminated mud on west and east margins, (b) a conformable sharp contact where the sand invades established mangrove environments which are underlain by bioturbated mud, (c) a conformable sharp contact where the sand has encroached onto a salt flat underlain by laminated mud.

Discussion.—The Point Torment Sand has been deposited only since tidal erosion has progressed to the stage onshore that Mowanjum Sand has been eroded. Thus it appears that the formation is the youngest in the area.

Modern Veneer

The term, Modern Veneer, is applied here to sediments that form a thin sheet over older units. It is not proposed to give it formational status, rather it is an informal term used here for descriptive purposes since the veener is largely ephemeral and is commonly stripped away seasonally.

The Mowanjum, Airport Creek, Double Nob and Christine Point formations, as well as Tertiary ironstone, crop out over extensive areas of eroded tidal flats where they are frequently covered seasonally by a veneer of recent sediment. Low tidal areas have a veneer of limestone pebbles that overlie the Airport Creek Formation from which they are derived, (Figs. 8A and 9). Other low tidal areas have a veneer of sand and shelly sand that overlies Airport Creek, Double Nob and (lower parts of) the Christine Point formations (Fig. 2). Low to mid-tidal areas have a veneer of interlayered mud and sand or a sheet of mud that overlies Christine Point Clay. Pockets and hollows in Tertiary rocks or Mowanjum Sand are covered by a veneer of sand, or sand/mud laminite or mud (Fig. 7).

All sedimentary veneers are less than 1 m thick and most are less than 30 cm thick. The veneers in low to mid tidal areas are frequently stripped on a monthly or seasonal basis by spring tides or storms. In the field shallow excavations or augering immediately distinguishes Modern Veneers from shoaling stratigraphic sequences of the Doctors Creek Formation.

Age of the units

The discussion on the ages of the stratigraphic units is best developed by beginning with an account of the youngest unit and proceeding through to progressively older units. The tentative age assignments of older units have necessarily been based on stratigraphic criteria.

Doctors Creek and Point Torment Formations, Modern Veneer.—The youngest units, Point Torment Sand, Doctors Creek Formation and the Modern Veneer are clearly contemporary. The older, buried Doctors Creek Formation that currently is being exposed by erosion is also assigned a Holocene age because its facies correspond to levels of the modern facies, the composition of fauna and flora (particularly type and size of mangrove stumps) are similar to modern biota and the preserved shelly fauna is fresh (i.e. unaltered). It would appear therefore that the Doctors Creek Formation and Point Torment Sand accumulated with mean sea level at about its present position.

Christine Point Clay.—The contact between the Christine Point Clay and Doctors Creek Formation is important stratigraphically and represents a major interval of

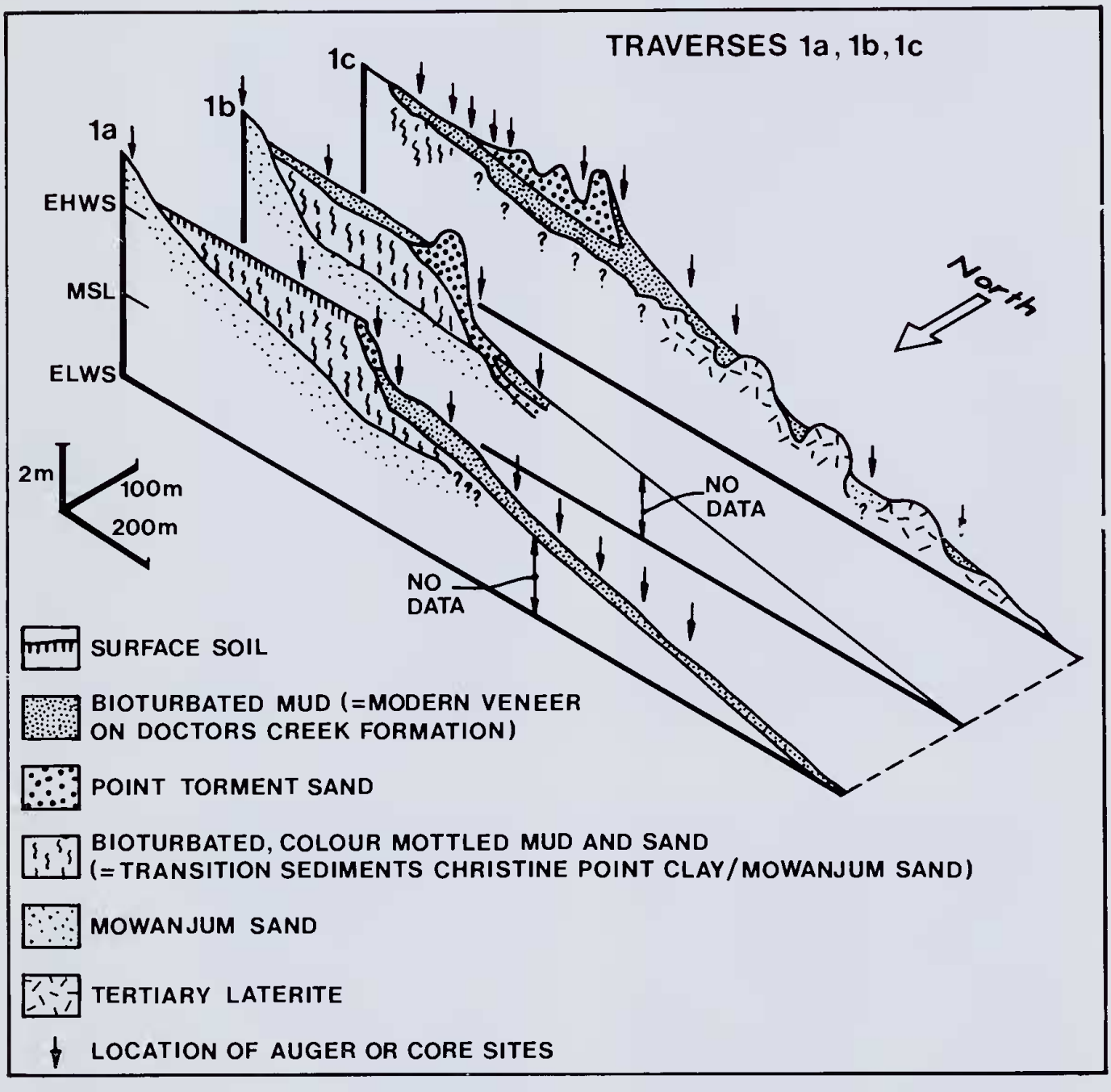

Figure 7.—Stratigraphy along 3 closely spaced transects 1a, 1b, 1c in the Black Rocks area. The profile illustrates the relationship between Point Torment Sand and the older stratigraphic units.

erosion where a large volume of sediment was removed. The following features suggest a pre-Holocene age: (a) it is a transgressive-regressive unit formed marginal to a sea whose mean level reached a maximum height of some 1·5 m *below* present mean sea level, (b) the mangrove stumps are distinctly larger (30 cm–1·2 m diameter) than those occurring both today and in the Doctors Creek Formation, (c) its shells (except for those preserved in carbonate nodules) have been lost through solution.

If both the Christine Point Clay and Doctors Creek Formation were of Holocene age the following sequence of events would be necessary: (a) inundation of a subaerial plain during the Holocene transgression, (b) encroachment and deposition of mangrove lithotope during the transgression to accumulate a 3–4 m thick mangrove mud sequence culminating, at the height of the transgression, in deposition of mid-tidal laminites, (c) a sea level still-stand, with mean sea level at about 1·5 m below present, so that the mangrove lithotope can prograde out over both mid-tidal laminites and the earlier deposited transgressive mangrove lithofacies, (d) local cementation by dolomite and magnesian calcite and selective dissolution of calcareous components in the Christine Point Clay, (e) extensive deep scouring of the now 6–8 m thick mangrove mud wedge and development of lag conglomerate of carbonate nodules, (f) rise of the sea to present mean sea level and deposition of shoaling tidal sequences (Doctors Creek Formation) within the embayments.

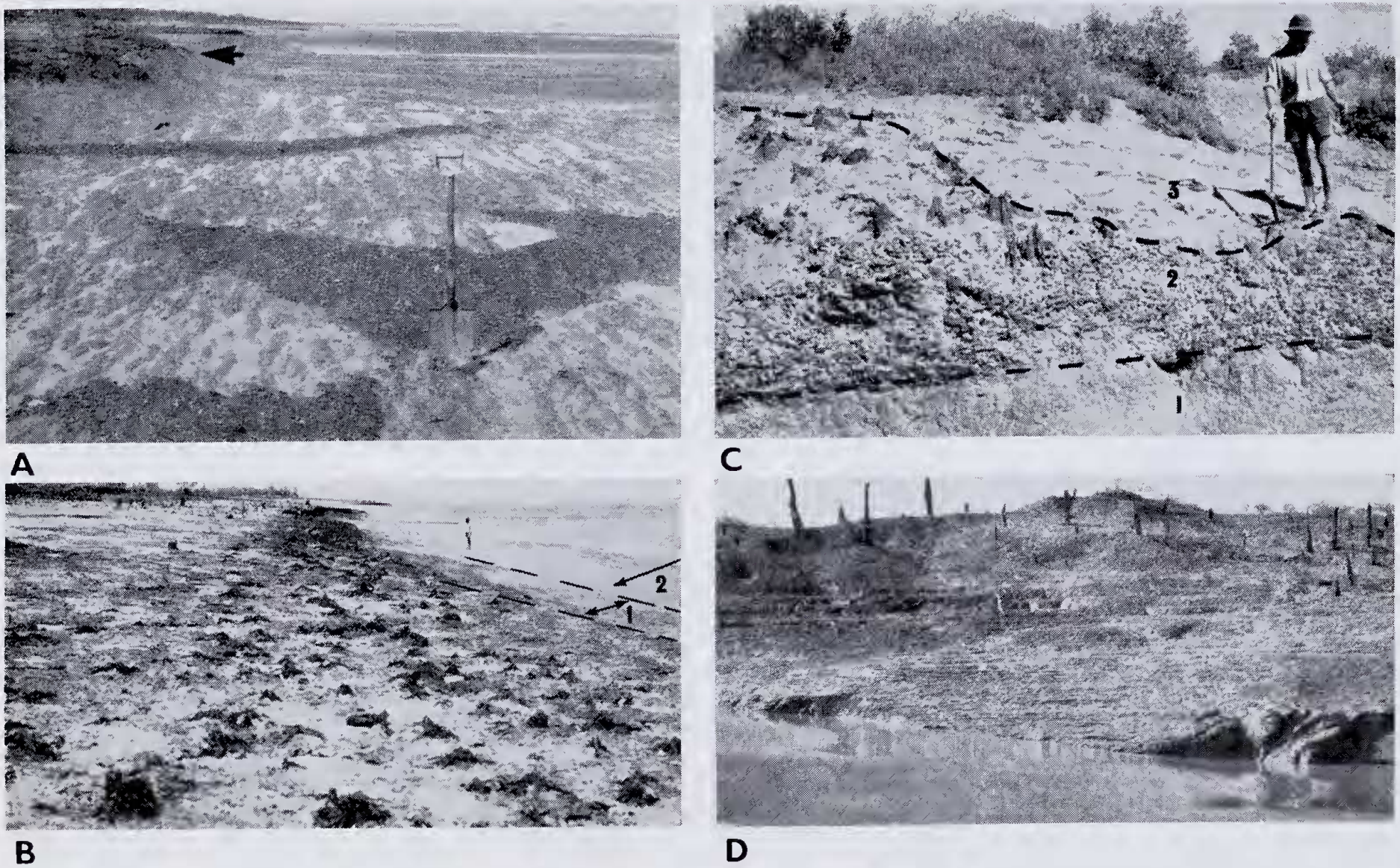

Figure 8.—A.—Tidal flats exposed by a low spring tide along transect 3. In the foreground is the Airport Creek Formation (linearly scoured by tidal erosion) with a patchy veneer of limestone-pebble conglomerate. At the base of the small cliff (Arrow) the Double Nob Formation separates the Airport Creek Formation from the overlying Christine Point Clay. Spade for scale is in foreground. B.—Tidal flat exposed by a low spring tide along transect 3. The Christine Point Clay with *in situ* mangrove stumps crops out over the inclined slope. The interval marked (1) is outcrop of Double Nob Formation which is exposed by low water neap tides; the interval marked (2) is outcrop of Airport Creek Formation. Man for scale. C.—Stratigraphic relationships exposed at headwaters of Airport Creek. Lowest exposed unit is Double Nob Formation (1). There is a sharp erosional contact between Doctors Creek Formation (3) and Christine Point Clay (2). Note mangrove stumps protruding above the unconformity into the overlying formation; compare this buried surface with Figure 8 B which is a contempory erosional surface. D.—Doctors Creek Formation exposed at low tide on the steep eroding banks of Doctors Creek. A segment of the stratigraphic sequence (sand/mud laminites overlain by bioturbated mud with *in situ Avicennia* mangrove stumps) is evident here. Height of cliff is approximately 4 m.

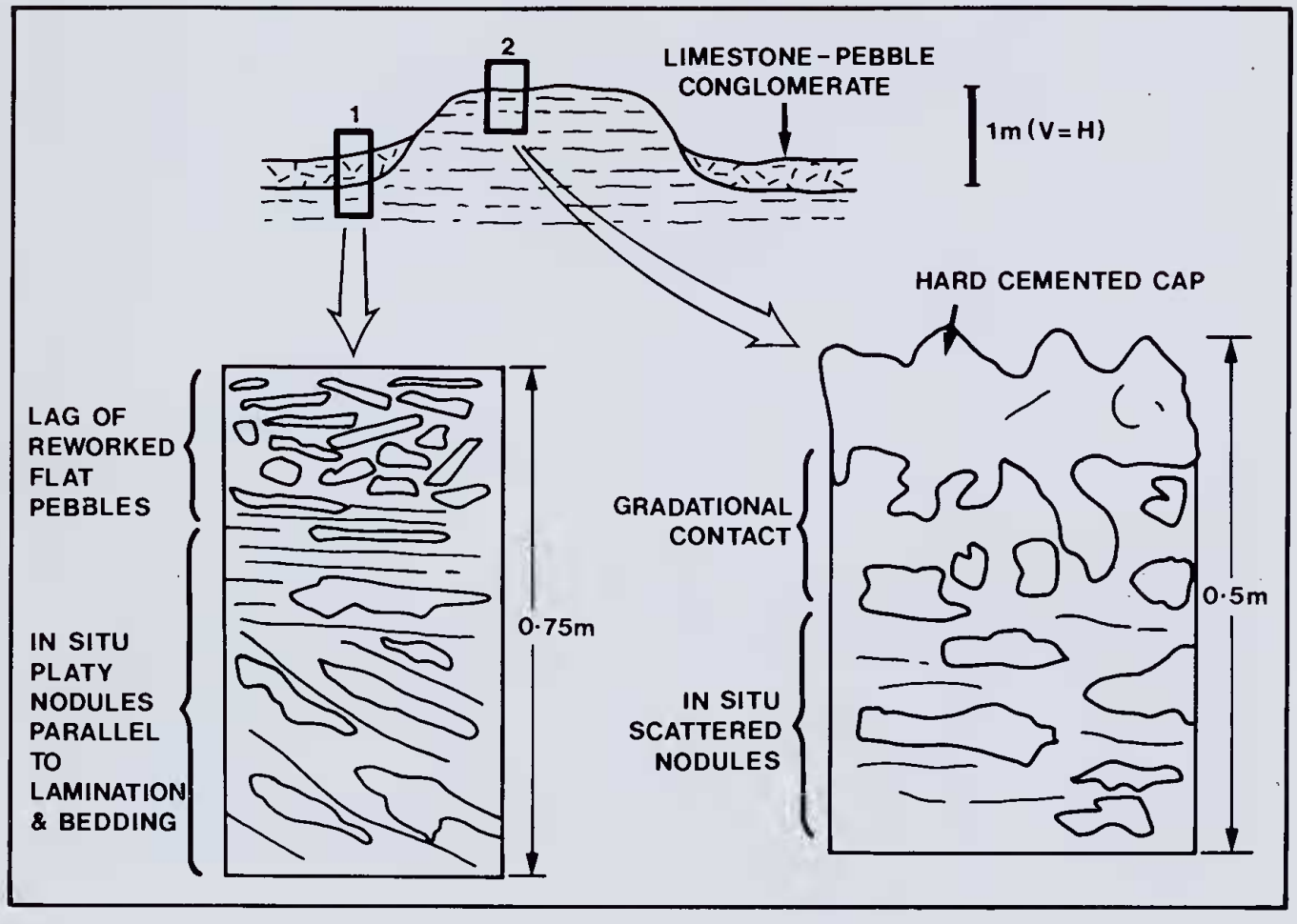

Figure 9.—Field sketch at western margin of transect 3 (Fig. 3) showing detail of geomorphology of tidal flat surface and stratigraphic relationships between Airport Creek Formation and Modern Veneer. Inset 1 shows relationship of Modern Veneer to Airport Creek Formation with *in situ* nodules; inset 2 shows disposition and extent of induration at top of Airport Creek Formation.

In view of the rate of the Holocene transgression determined by other workers (Curray 1965, Fairbridge 1961, Milliman and Emery 1968) and the lack of a mean sea level still stand at approximately 1·5 m below present in the world literature it would appear unlikely that all these events took place in the Holocene. It is concluded here that the Christine Point Clay is a late Pleistocene marine unit and the Doctors Creek Formation is Holocene. The timing of the extensive erosion of Christine Point Clay is unknown. If the erosion was subaerial and developed prior to deposition of Doctors Creek Formation, then subsequent Holocene transgression flooded the subaerially scoured embayments. The Doctors Creek Formation then would have filled the embayments in much the same way it is accumulating today. If on the other hand the scouring was brought about by tidal erosion, then the embayments would have formed during the Holocene transgression and erosion has continued sometime up to the stage when the sea reached its present level.

Double Nob and Airport Creek Formations.—The Double Nob Formation is interpreted as a Pleistocene palaeosol formed in a similar environment to black soil plains. The formation occurs as a gently undulating sheet some 2·5–3 m below present mean sea level and obviously in the past it formed the subaerial surface of a savannah plain. It predates the Christine Point Clay and was developed by degradation of the calcareous tidal sediments of the Airport Creek Formation. Sediments of the Airport Creek Formation would have been deposited during an earlier marine incursion and the soil formed during the subsequent subaerial period.

Mowanjum Sand.—From its stratigraphic relationships the Mowanjum Sand predates all 3 marine Quaternary units. Although the Mowanjum Sand was emplaced as the first Quaternary unit in the area, its seaward margin has been repeatedly reworked and therefore it *appears* to interfinger with all the other younger marine units. Glacial periods (or sea level lows) of the Pleistocene are represented as an unconformity between the three marine units. The tongues of Mowanjum Sand extend along the unconformities that separate marine units.

Carbon dating.—Carbon dating of mangrove stumps has been carried out in this area by Jennings and Coventry (1973) and by Jennings (1975). Wood from the Doctors Creek Formation gave ages of about 5 840–7 450 years B.P. (Jennings 1975). Although carbon-14 dating in mangrove sediments can be somewhat tenuous, these dates essentially agree with the assignment of the Doctors Creek Formation using stratigraphic criteria to a Holocene age. Jennings and Coventry (1973) dated mangrove stumps under sand spits (Point Torment Sand) at 500–1 190 years B.P. This gives an indication of when the Point Torment Sand was first emplaced; it agrees with the conclusion, deduced from stratigraphic criteria that the formation is the youngest in the area.

If the carbon-14 dating can be relied upon then it appears that for the Christine Point Clay to be Holocene, it would have to be *deposited and eroded* in the interval of 7 500–12 000 years B.P., a period generally conceded to be a time of rapidly rising sea levels. The conclusion reached here is that the Christine Point Clay is of late Pleistocene age.

Conclusions

Six major Quaternary formations are recognised underlying the tidal flats of King Sound. The oldest unit, termed the Mowanjum Sand, is a formation of red sand that forms the hinterland of King Sound. The subsequent succession consists of four marine units separated by unconformities; their contact is marked by soils or large scale erosional interfaces. Three units were deposited in tidal flat environments but each is lithologically distinct. The oldest Pleistocene marine unit is called the Airport Creek Formation; a soil, the Double Nob Formation, separates it from the overlying, Christine Point Clay, also Pleistocene in age. A Holocene unit, the Doctors Creek Formation, fills large-scale hollows or embayments erosionally cut into the Pleistocene units. The youngest unit, the Point Torment Sand is a shoreline deposit largely formed where tidal erosion has cut the tidal flats back into the hinterland formed of Mowanjum Sand.

Today in areas where erosion is dominant the older Pleistocene formations crop out on the tidal flats. Here they are either exposed or are covered by a Modern Veneer that is frequently stripped away. Thus much of the tidal flats represents an eroding unconformity surface. The Holocene Doctors Creek Formation is also being eroded in most localities where it is present.

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